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RTCC REQUIREMENTS FOR MISSION G: NONFREE-RETURN MODES OF THE TRANSLUNAR MIDCOURSE CORRECTION PROCESSOR

Lunar Mission Analysis Branch

MISSION PLANNING AND ANALYSIS DIVISION

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PROJECT APOLLO

RTCC REQUIREMENTS FOR MISSION G: NONFREE-RETURN MODES OF THE TRANSLUNAR MIDCOURSE CORRECTION PROCESSOR

By Quentin A. Holmes
Lunar Mission Analysis Branch

February 28, 1969

MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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RTCC REQUIREMENTS FOR MISSION G:

NONFREE-RETURN MODES OF THE

TRANSLUNAR MIDCOURSE CORRECTION PROCESSOR

By Quentin A. Holmes

SUMMARY AND INTRODUCTION

There are two situations in which it is desirable to relax the free-return constraint on translunar trajectories. The first situation occurs when translunar injection is so far from nominal that a lunar orbital mission which uses free-return trajectories is impossible. For some of these cases, it is possible to salvage a lunar orbital mission by the use of a nonfree-return trajectory. The second, and more interesting, situation occurs in the hybrid mission profile (ref. 1). In this profile, the TLI maneuver is made to place the spacecraft on a free-return trajectory with a high pericynthion altitude; after transposition and docking is completed, a planned midcourse maneuver is made which transfers the spacecraft to a nonfree-return trajectory with a pericynthion altitude of approximately 60 n. mi. Compared to free-return missions, the hybrid profile affords substantial performance gains because the spacecraft travels slower at the start of LOI and because ϕ_{pc} is less constrained.

The nonfree BAP options of the real-time midcourse processor are designed to meet these needs. Two distinct options are available: option 4, a fixed orbit nonfree-return BAP; and option 5, a free orbit nonfree-return BAP. Revisions of the formulation presented in reference 2 for options 4 and 5 are presented in the flow diagrams. The new formulation is based on the vector offset method for simulation of integrated trajectories with a conic trajectory computer. This technique makes it possible to reoptimize rapidly and accurately a lunar mission during a translunar coast.

ABBREVIATIONS

AZM	azimuth
BAP	best adaptive path
DPS	descent propulsion system
G.m.t.	Greenwich mean time
HT	height
INCL	inclination
INT	integrated
LAT	latitude
LONG	longitude
LLS	lunar landing site
LM	lunar module
LOI	lunar orbit insertion
LPO	lunar parking orbit
MCC	midcourse correction
MED	manual entry device
PC	plane change
RTCC	Real-Time Computer Complex
SEA	sun elevation angle
SPS	service propulsion system
TEI	transearth injection
TLI	translunar injection
TLMC	first guess logic (backward iterator) for ΔV, $\Delta\gamma$, $\Delta\psi$ of the mission maneuver

SYMBOLS

r	radius
S'	auxiliary state
X, Y, Z	Cartesian components of position vector
$\dot{X}, \dot{Y}, \dot{Z}$	Cartesian components of velocity vector
v	velocity
γ	flight-path angle
ψ	azimuth
Δ	change
T	time

Subscripts:

pc	pericynthion
nd	node
I	integrated

TRANSLUNAR FLIGHT TIME

Specification of pericynthion latitude and altitude does not determine translunar flight time on a nonfree-return trajectory. Lack of need for these specifications plays a key role in the performance gains afforded by nonfree-return trajectories. The range of acceptable flight times is determined by two considerations. The first consideration is crew safety, and the second consideration is proper lighting at the time of lunar landing. Translunar flight time is closely associated with pericynthion position and velocity. For a given inclination at pericynthion, time to the node can be bounded (min ΔT_{DPS}, max ΔT_{DPS}) to enforce the DPS abort constraint. If the range is not violated, then the LM DPS has the ability to transfer the spacecraft to a free-return trajectory shortly after pericynthion is passed. Sun elevation at lunar landing is determined by the

G.m.t. of LM touchdown. The acceptable range of SEA at lunar landings is entered as a range in G.m.t. The corresponding limits (min ΔT_{SEA}, max ΔT_{SEA}) for time to the node are obtained by use of the nominal delta time in LPO to first pass. The range used by the program insures that both the DPS and the lighting constraints are satisfied. The upper and lower limits on translunar flight time can be overridden by a MED.

A polynomial $\delta(\Delta T)$ is used to predict the optimum time to the node. This polynomial (ref. 3) was constructed for use with midcourse corrections that occur within 20 hours of TLI; it is used in the first guess logic whenever the value that it predicts falls within the range of acceptable values. The difference between nominal time of the node and expected time of the node δT is used to estimate pericynthion velocity and longitude to start the first guess logic.

METHOD

The underlying assumption of the vector offset method is that the difference between two conic trajectories is a close approximation of the difference between the corresponding pair of integrated trajectories. For full mission optimization, a velocity offset is applied at each end of the translunar trajectory. This permits the MCC, LOI, PC, and TEI maneuvers to be optimized as a set by the use of conic trajectories. Moreover, the resultant nodal conditions (H_{nd}, ϕ_{nd}, λ_{nd}, T_{nd}) are optimum for integrated trajectories.

Based on a state vector in translunar coast, a midcourse maneuver is computed to transfer the spacecraft to a conic trajectory which satisfies all mission constraints (full mission select). Next, an integrated midcourse maneuver is targeted to the conic node.

As far as the midcourse maneuver is concerned, the discrepancy between conic and integrated trajectories is reflected in the difference in their respective midcourse maneuvers ($\Delta\dot{X}$, $\Delta\dot{Y}$, $\Delta\dot{Z}$). An auxiliary state S' is built according to

$$S' = S2C - \Delta\dot{X}_I - \Delta\dot{Y}_I - \Delta\dot{Z}_I \tag{1}$$

where $S2C$ is the state vector that results after the conic midcourse and where $\Delta\dot{X}_I$, $\Delta\dot{Y}_I$, $\Delta\dot{Z}_I$ are integrated values. Prior to optimization

S' is substituted for the premidcourse state; the ΔV, $\Delta\gamma$, and $\Delta\psi$ required to regain S2C are computed and are used as first guesses for the midcourse maneuver.

At LOI, the discrepancy between conic and integrated trajectories is only in the magnitude and direction of their respective velocity vectors at the common node.

A velocity offset ($\Delta\dot{X}''$, $\Delta\dot{Y}''$, $\Delta\dot{Z}''$) at LOI is computed according to

$$\Delta\dot{X}'' = (S3I - S3C)_{\dot{x}} \text{ component} \tag{2}$$

$$\Delta\dot{Y}'' = (S3I - S3C)_{\dot{y}} \text{ component} \tag{3}$$

$$\Delta\dot{Z}'' = (S3I - S3C)_{\dot{z}} \text{ component} \tag{4}$$

During optimization, the offset is made available to the trajectory computer. After conic propagation to the node, the offset is applied before the LOI maneuver is computed. This offset permits a coupled full-mission optimization of the midcourse correction, the LOI maneuver, lunar orbit plane change, and transearth injection to be performed using conic trajectories.

Because the translunar flight time changes due to optimization, the original offsets may be slightly in error. This error is manifested as a difference between the predicted and the actual characteristic velocities of the MCC and LOI maneuvers. When appropriate, revised offsets are built with the new end conditions, and the optimization is repeated.

OPTION 4 - FIXED ORBIT NONFREE-RETURN BAP

The steps involved in computation of a nonfree-return BAP with a fixed lunar orbit are shown in flow chart 1. The principal changes from the flow chart given in reference 2 are the use of offset vectors during the conic optimization and the introduction of an integrated XYZ and t step (needed to build the offsets) immediately after conic full mission select. In addition, flight-path angle at the start of LOI was deleted from the independent variable array. The program exits if the characteristic velocities predicted for the MCC and LOI are within 1 fps of the integrated MCC and LOI maneuvers. Otherwise, new offsets are computed and optimization is repeated. Only one such recycle is permitted.

OPTION 5 - FREE ORBIT NONFREE-RETURN BAP

Analogous changes were made to the free orbit nonfree-return BAP. In addition, flight-path angle at the start of LOI was deleted from the independent variable array during optimization. The steps involved in the computation of a nonfree-return BAP with a free lunar parking orbit are given in flow chart 2.

Option 4: Fixed orbit nonfree-return BAP

Enter with state vector and delay time to MCC

↓

Step 1

Converge conic TLMC by use of nominal pericynthion state

Independent variables	Value	Step size	Weight
Scalar velocity at pericynthion	**	ϕ 1564	512
Azimuth at pericynthion	270°	ϕ 1564	512
Longitude at pericynthion	***	ϕ 1564	512

Time of pericynthion min[max DPS time, MAX SEA time, $\delta(\Delta T)$] Not triggered

Dependent variables	Minimum	Maximum	Class designator
X	Premidcourse	±0.0657 n. mi.	1
Y	Premidcourse	±0.0657 n. mi.	1
Z	Premidcourse	±0.0657 n. mi.	1

** computed as $\nu = \sqrt{.18406305 + .5530824/r_{pc}} - .0022(\delta T)$

*** computed as $\lambda = 3.1 - 0.25(\delta T)$

Flow chart 1.- Fixed orbit nonfree-return BAP

A

Step 2

Coverge a conic full mission (select mode only)

Independent variables	Value	Step size	Weight
Delta azimuth TEI	Nominal	ϕ 1544	8
Delta velocity TEI	Nominal	ϕ 1544	1
Time in lunar orbit	Nominal	ϕ 1544	10^{-6}
Delta time to 1st pass	Nominal	ϕ 1574	10^{-3}
Delta azimuth LOI	Nominal	ϕ 1564	1
Delta azimuth MCC	Step 1	ϕ 1564	8
Delta gamma MCC	Step 1	ϕ 1544	8
Delta velocity MCC	Step 1	ϕ 1544	8

Dependent variables	Minimum	Maximum	Weight	Class designator
HT of pericynthion	40 n. mi.	100 n. mi.	1	0
INCL of pericynthion	90°	182°	64	0
HT of lunar obrit	Nominal	±.5° n. mi.	--	1
LAT of lunar landing site	Nominal	±.01°	--	1
LONG of lunar landing site	Nominal	±.01°	--	1
AZM over lunar landing site	Nominal	±.01°	--	1
Delta time to node	Lower limit: max(min ΔT_{DPS}, Min ΔT_{sea}) -2 hr; Upper limit: min(max ΔT_{DPS}, Max ΔT_{sea}) +2 hr		0.125	0
Transearth flight time	(Nominal $-\delta T$)	±8 hr	0.125	0
INCL of powered return	0°	40°	0.125	0
Delta long of earth landing	-0.2°	+0.2°	--	1
HT of entry	Nominal	±1.735 n. mi.	--	1

B

Flow Chart 1.- Continued.

B

Store conic postmidcourse state (S2C) and conic state at start of LOI (S3C)

Step 3

Converge integrated TLMC by use of nodal state from step 2

Independent variables	Value	Step size	Weight
Scalar velocity at the node	Step 2	ϕ 1564	512
Azimuth at the node	Step 2	ϕ 1564	512
Longitude of the node	Step 2	ϕ 1564	512
Time of the node	Step 2	Not triggered	

Dependent variables	Minimum	Maximum	Class designator
X	Premidcourse position	±0.657 n. mi.	1
Y	Premidcourse position	±0.657 n. mi.	1
Z	Premidcourse position	±0.657 n. mi.	1

Step 4

Converge a precision trajectory to the node obtained in step 2

Independent variables	Value	Step size	Weight
Delta azimuth MCC	Step 3	ϕ 1544	512
Delta gamma MCC	Step 3	ϕ 1544	512
Delta velocity MCC	Step 3	ϕ 1524	512
Time of the node	Step	Not triggered	

Dependent variables

HT of node	Step 2	±0.5 n. mi.	--	1
LAT of node	Step 2	±0.01°	--	1
LONG of node	Step 2	±0.01°	--	1
INCL of pericynthion	90°	182°	64	0

C

Flow chart 1.- Continued.

C

Store INT midcourse maneuver $\Delta\dot{X}_I$, $\Delta\dot{Y}_I$, $\Delta\dot{Z}_I$
Store INT state at start of LOI (S3I)

Compute velocity offsets and first guesses

Program needs:

For MCC offset;

S1 - premidcourse state
S2C - conic postmidcourse state

$\Delta\dot{X}_I$, $\Delta\dot{Y}_I$, $\Delta\dot{Z}_I$ - integrated midcourse correction

(a) $S' = S2C - \Delta\dot{X}_I - \Delta\dot{Y}_I - \Delta\dot{Z}_I$

(b) new first guesses $\Delta V'$, $\Delta\gamma'$, $\Delta\psi'$ for the MCC variables according to $S2C = S'$ (polar form) $+ \Delta V' + \Delta\gamma' + \Delta\psi'$

For LOI offset;

S3C - conic state at the start of LOI

S3I - INT state at the start of LOI

(c) $\Delta\dot{X}'' = (S3I - S3C)_{\dot{x}}$ component
$\Delta\dot{Y}'' = (S3I - S3C)_{\dot{y}}$ component
$\Delta\dot{Z}'' = (S3I - S3C)_{\dot{z}}$ component

D

Flow chart 1.- Continued.

D

Step 5

With conic trajectories, optimize mass after TEI by use of S' as the state vector and by offset of the state at start of LOI prior to computation of LOI maneuver.

Independent variables	Value	Step size	Weight
Delta azimuth TEI	Step 2	ϕ 1544	8
Delta velocity TEI	Step 2	ϕ 1544	1
Time in lunar orbit	Step 2	ϕ 1544	10^{-6}
Delta time to 1st pass	Step 2	ϕ 1574	10^{-3}
Delta azimuth LOI	Step 4	ϕ 1564	1
Delta azimuth MCC	$\Delta\psi'$	ϕ 1564	512
Delta gamma MCC	$\Delta\gamma'$	ϕ 1544	512
Delta velocity MCC	$\Delta V'$	ϕ 1544	512

Dependent variables	Minimum	Maximum	Weight	Class designator
HT of pericynthion	40 n. mi.	100 n. mi.	1	0
INCL of pericynthion	90°	182°	64	0
HT of lunar orbit	Step 2	±0.5 n. mi.	--	1
LAT of lunar landing site	Nominal	±0.01°	--	1
LONG of lunar landing site	Nominal	±0.01°	--	1
AZM over lunar landing	Nominal	±0.01°	--	1
Delta time to node	Lower limit: max (min ΔT_{DPS}, Min ΔT_{sea})	Upper limit: min (max ΔT_{DPS}, max ΔT_{sea})	0.125	0
INCL of powered return	0°	40°	0.125	0
Delta LONG of earth landing	-0.2°	+0.02°	--	1
HT of entry	Nominal	±1.735 n. mi.	--	1
Mass after TEI	min = step 2 + 3000 lb = max		--	-1

E

Flow chart 1.- Continued.

E

Did mass after TEI increase by more than 2600 lb during optimization?

YES → D

NO

Store conic postmidcourse state (S2C) and conic state at start of LOI (S3C)

Step 6

Converge integrated TLMC by use of the nodal state from step 5

Independent variables	Value	Step size	Weight
Scalar velocity at the node	Step 5	ϕ 1564	512
Azimuth at the node	Step 5	ϕ 1564	512
Longitude of the node	Step 5	ϕ 1564	512
Time of the node	Step 5	Not triggered	

Dependent variables	Minimum	Maximum	Class designator
X	Premidcourse position	±0.657 n. mi.	1
Y	Premidcourse position	±0.657 n. mi.	1
Z	Premidcourse position	±0.657 n. mi.	1

Step 7

Converge a precision trajectory to the node obtained in step 5

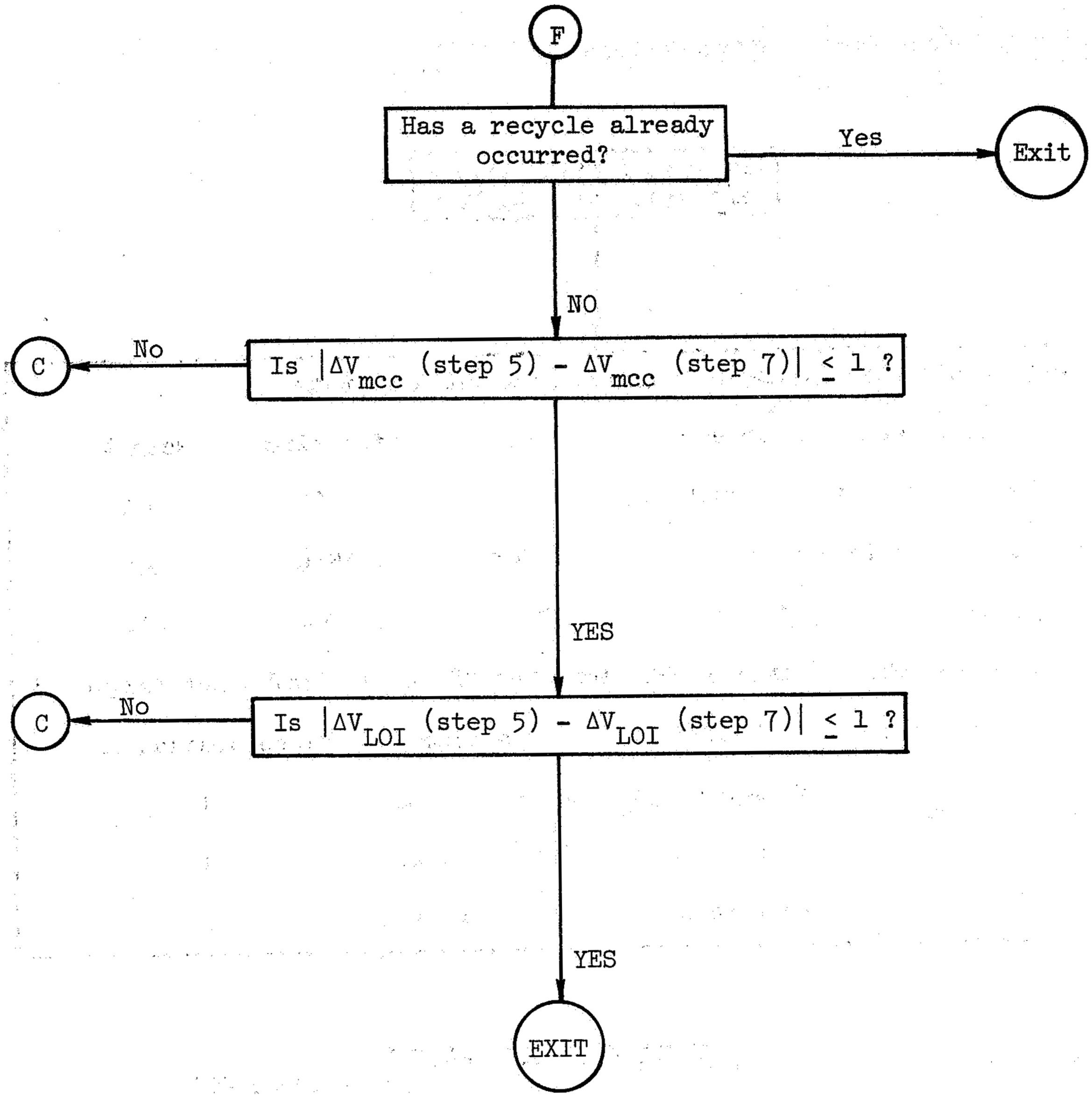
Independent variables	Value	Step size	Weight
Delta azimuth MCC	Step 6	ϕ 1544	512
Delta gamma MCC	Step 6	ϕ 1544	512
Delta velocity MCC	Step 6	ϕ 1524	512
Time of the node	Step 5	Not triggered	

Dependent variables

HT of node	Step 5	±0.5 n. mi.	--	1
LAT of node	Step 5	±0.01°	--	1
LONG of node	Step 5	±0.01°	--	1
INCL of pericynthion	90°	182°	64	0

F

Flow chart 1.- Continued.



Flow chart 1.- Concluded.

Option 5: Free orbit nonfree-return BAP

Enter with state vector and delay time to MCC

↓

Step 1

Converge conic TLMC by use of nominal pericynthion state

Independent variables	Value	Step size	Weight
Scalar velocity at pericynthion	**	ϕ 1564	512
Azimuth at pericynthion	270°	ϕ 1564	512
Longitude at pericynthion	***	ϕ 1564	512
Time of pericynthion	min[max DPS time, MAX SEA time, δ(ΔT)]		Not triggered

Dependent variables	Minimum	Maximum	Class designator
X	Premidcourse	±0.0657 n. mi.	1
Y	Premidcourse	±0.0657 n. mi.	1
Z	Premidcourse	±0.0657 n. mi.	1

** computed as $\nu = \sqrt{.18406305 + .5530824/r_{pc}} - .0022(\delta T)$

*** computed as $\lambda = 3.1 - 0.25(\delta T)$

Flow chart 2.- Free orbit nonfree return BAP

A

Step 2

Coverge a conic full mission (select mode only)

Independent variables	Value	Step size	Weight
Delta azimuth TEI	0	ϕ 1544	8
Delta velocity TEI	Nominal	ϕ 1544	1
Time in lunar orbit	Nominal	ϕ 1544	10^{-6}
Delta time to 1st pass	Nominal	ϕ 1574	10^{-3}
Delta azimuth LOI	0	ϕ 1564	1
Delta azimuth MCC	Step 1	ϕ 1564	8
Delta gamma MCC	Step 1	ϕ 1544	8
Delta velocity MCC	Step 1	ϕ 1544	8

Dependent variables	Minimum	Maximum	Weight	Class designator
HT of pericynthion	40 n. mi.	100 n. mi.	1	0
INCL of pericynthion	90°	182°	64	0
HT of lunar obrit	Nominal	±.5° n. mi.	--	1
LAT of lunar landing site	Nominal	±.01°	--	1
LONG of lunar landing site	Nominal	±.01°	--	1
AZM over lunar landing site	Nominal (MED)	±.01°	--	1
Delta time to node	Lower limit: max(min ΔT_{DPS}, Min ΔT_{sea}) -2 hr	Upper limit: min(max ΔT_{DPS}, Max ΔT_{sea}) +2 hr	0.125	0
Transearth flight time	(Nominal $-\delta T$)	±8 hr	0.125	0
INCL of powered return	0°	40°	0.125	0
Delta long of earth landing	-0.2°	+0.2°	--	1
HT of entry	Nominal	±1.735 n. mi.	--	1

B

Flow chart 2.- Continued.

B

Store conic postmidcourse state (S2C) and conic state at start of LOI (S3C)

Step 3

Converge integrated TLMC by use of nodal state from step 2

Independent variables	Value	Step size	Weight
Scalar velocity at the node	Step 2	ϕ 1564	512
Azimuth at the node	Step 2	ϕ 1564	512
Longitude of the node	Step 2	ϕ 1564	512
Time of the node	Step 2	Not triggered	

Dependent variables	Minimum	Maximum	Class designator
X	Premidcourse position	±0.657 n. mi.	1
Y	Premidcourse position	±0.657 n. mi.	1
Z	Premidcourse position	±0.657 n. mi.	1

Step 4

Converge a precision trajectory to the node obtained in step 2

Independent variables	Value	Step size	Weight
Delta azimuth MCC	Step 3	ϕ 1544	512
Delta gamma MCC	Step 3	ϕ 1544	512
Delta velocity MCC	Step 3	ϕ 1524	512
Time of the node	Step	Not triggered	

Dependent variables

HT of node	Step 2	±0.5 n. mi.	--	1
LAT of node	Step 2	±0.01°	--	1
LONG of node	Step 2	±0.01°	--	1
INCL of pericynthion	90°	182°	64	0

C

Flow chart 2.- Continued.

C

Store INT midcourse maneuver $\Delta\dot{X}_I$, $\Delta\dot{Y}_I$, $\Delta\dot{Z}_I$

Store INT state at start of LOI (S3I)

Compute velocity offsets and first guesses

Program needs:

For MCC offset;

S1 - premidcourse state

S2C - conic postmidcourse state

$\Delta\dot{X}_I$, $\Delta\dot{Y}_I$, $\Delta\dot{Z}_I$ - integrated midcourse correction

(a) $S' = S2C - \Delta\dot{X}_I - \Delta\dot{Y}_I, \Delta\dot{Z}_I$

(b) new first guesses $\Delta V'$, $\Delta\gamma'$, $\Delta\psi'$ for the MCC variables according to $S2C = S'$ (polar form) $+ \Delta V' + \Delta\gamma' + \Delta\psi'$

For LOI offset;

S3C - conic state at the start of LOI

S3I - INT state at the start of LOI

(c) $\Delta\dot{X}'' = (S3I - S3C)_{\dot{x}}$ component

$\Delta\dot{Y}'' = (S3I - S3C)_{\dot{y}}$ component

$\Delta\dot{Z}'' = (S3I - S3C)_{\dot{z}}$ component

D

Flow chart 2.- Continued.

D

Step 5

With conic trajectories, optimize mass after TEI by use of S' as the state vector and by offset of the state at start of LOI prior to computation of LOI maneuver.

Independent variables	Value	Step size	Weight
Delta azimuth TEI	Step 2	ϕ 1544	8
Delta velocity TEI	Step 2	ϕ 1544	1
Time in lunar orbit	Step 2	ϕ 1544	10^{-6}
Delta time to 1st pass	Step 2	ϕ 1574	10^{-3}
Delta azimuth LOI	Step 4	ϕ 1564	1
Delta azimuth MCC	$\Delta\psi'$	ϕ 1564	512
Delta gamma MCC	$\Delta\gamma'$	ϕ 1544	512
Delta velocity MCC	$\Delta V'$	ϕ 1544	512

Dependent variables	Minimum	Maximum	Weight	Class designator
HT of pericynthion	40 n. mi.	100 n. mi.	1	0
INCL of pericynthion	90°	182°	64	0
HT of lunar orbit	Step 2	±0.5 n. mi.	--	1
LAT of lunar landing site	Nominal	±0.01°	--	1
LONG of lunar landing site	Nominal	±0.01°	--	1
AZM over lunar landing site	MED	MED	1	0
Delta time to node	Lower limit: max (min ΔT_{DPS}, Min ΔT_{sea})	Upper limit: min (max ΔT_{DPS}, max ΔT_{sea})	0.125	0
INCL of powered return	0°	40°	0.125	0
Delta LONG of earth landing	-0.2°	+0.02°	--	1
HT of entry	Nominal	±1.735 n. mi.	--	1
Mass after TEI	min = step 2 + 3000 lb = max		--	-1

E

Flow chart 2.- Continued.

E

Did mass after TEI increase by more than 2500 lb during optimization?

YES → D

NO

Store conic postmidcourse state (S2C) and conic state at start of LOI (S3C)

Step 6

Converge integrated TLMC by use of the nodal state from step 5

Independent variables	Value	Step size	Weight
Scalar velocity at the node	Step 5	ϕ 1564	512
Azimuth at the node	Step 5	ϕ 1564	512
Longitude of the node	Step 5	ϕ 1564	512
Time of the node	Step 5	Not triggered	

Dependent variables	Minimum	Maximum	Class designator
X	Premidcourse position	±0.657 n. mi.	1
Y	Premidcourse position	±0.657 n. mi.	1
Z	Premidcourse position	±0.657 n. mi.	1

Step 7

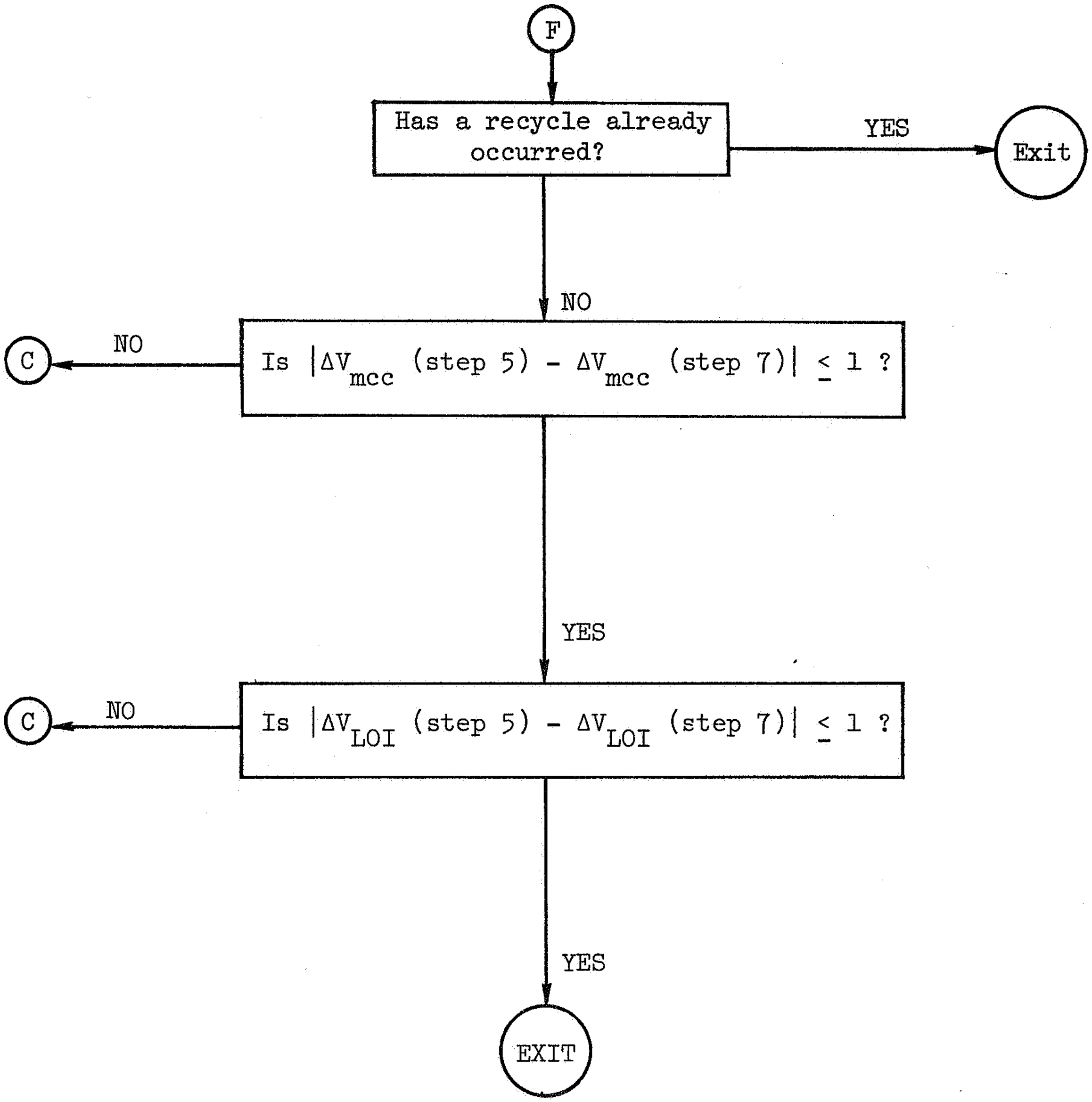
Converge a precision trajectory to the node obtained in step 5

Independent variables	Value	Step size	Weight
Delta azimuth MCC	Step 6	ϕ 1544	512
Delta gamma MCC	Step 6	ϕ 1544	512
Delta velocity MCC	Step 6	ϕ 1524	512
Time of the node	Step 5	Not triggered	

Dependent variables				
HT of node	Step 5	±0.5 n. mi.	--	1
LAT of node	Step 5	±0.01°	--	1
LONG of node	Step 5	±0.01°	--	1
INCL of pericynthion	90°	182°	64	0

F

Flow chart 2.- Continued.



Flow chart 2.- Concluded.

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